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bonded to maxillary incisors with severe wear: effect of preparation design
and material type**

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**Load bearing capacity of minimal invasive direct and indirect veneers bonded to maxillary incisors
with severe wear: Effect of preparation design and material type**

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Abstract: This study evaluated the load bearing capacity of direct and indirect veneers versus full-coverage crowns and classified the failure types after fracture load. Sound human maxillary incisors (N=108, n=12 per group) were randomly divided into nine groups to receive one of the following restoration types: Group 1: Intact tooth, Group 2: Direct resin composite, Group 3: Lingual: Indirect composite veneer, Labial: Ceramic veneer, Lingual overlap: Ceramic, Group 4: Lingual: Indirect composite, Labial: Ceramic, Lingual overlap: Indirect composite, Group 5: Lingual: Direct composite, Labial: Ceramic, Group 6: Lingual: Ceramic, Labial: Ceramic, Group 7: Feldspathic ceramic crown, Group 8: Metal-ceramic Crown, Group 9: Lithium disilicate crown. Teeth were prepared simulating the erosion/wear conditions in each group. After cementing, the specimens were stored in distilled water at 37°C for 2 months and then loaded to failure from the lingual surface at 105° inclination in the Universal Testing Machine (1 mm/min). Failure types were classified as irreparable or repairable. Data were analyzed using one-way ANOVA, Sheffe and Bonferroni tests ($\alpha=0.05$). Mean fracture strength (N) of Groups 1, 4, 8, and 9 (558 ± 278 - 880 ± 319) were significantly higher than those of other groups (348 ± 101 - 421 ± 162) ($p<0.05$). Lingual veneering with direct/indirect resin composite or ceramic did not significantly affect the results ($p>0.05$) but lingual overlap with indirect composite increased the results ($p<0.05$). Group 1, 2, 4 and 5 presented more repairable failures. Restoration of eroded teeth could best be achieved with direct composite veneer at the lingual and ceramic veneer on the labial surface.

Keywords: Erosion; Laminates; Minimal invasive; Static loading; Veneers; Wear.

Introduction

Today, acceptance of malformed or severely worn anterior teeth is steadily decreasing as a result of growing aesthetic demands [1]. While no evidence for the increasing prevalence of malformations exists, substance loss caused by tooth wear or erosion is rising [2-3]. However, reports on the prevalence and severity of tooth wear with different etiologies, often use different indices [4-6]. Nevertheless, severely worn anterior dentition requires restorations not only due to poor aesthetic appearance but also to prevent further substance loss that often results in loss of vertical dimension. Anterior teeth could also show compensatory eruption, apical cementum deposition and localized alveolar bone growth depending on the number of posterior teeth [2,7].

Traditionally, severely worn teeth are restored with full-coverage with crowns, either made of porcelain fused to metal (PFM) or all-ceramic materials without metal framework where the latter could be made of glass-infiltrated alumina, densely sintered zirconia or lithium disilicate ceramics [8,9]. Both treatment modalities present survival rates of 95.6% after 5 years clinical function [9] and 97.4, 94.8 and 95.5% after 5, 8 and 10 years, respectively [10]. Unfortunately, crowns are still considered invasive restoration options since they require four times more substance removal compared to additive methods using resin composites or ceramic veneer reconstructions [11]. Likewise, crowns present possible vitality loss between 2 to 8 % after 5 or 10-year clinical function, respectively [9,12] decrease in gingival crevicular fluid rate and increase inflammation of gingival tissues [13]. Moreover, anterior teeth restored with single crowns show higher retreatment rate than posterior teeth [14].

The introduction of modern multi-step adhesive systems provided a broader plethora of treatment options for restoring worn teeth. The possibility of etching and conditioning enamel and dentin and the introduction of restorative materials such as indirect resin composites or ceramics, resulted in more conservative, mainly additive treatment methods compared to the conventional crown preparation. Direct or indirect minimal invasive options made of resin based composites, various ceramics or a combination of both, require different types of preparations ranging from no preparation to minimal invasive and more extended preparations. Both direct and indirect restoration options, deliver similar adhesion results on tooth substance when conditioned

Accordingly [15]. Yet, minimal invasive preparations, may remain solely in enamel, dentin and often in a combination of them both, creating a challenging situation in bonding [16,17].

Survival rates of resin composite materials consisting micro- or nano-hybrid fillers on the monomer matrix is limited from 3 to 6 years observation time [18-21]. One clinical study presented 10 year survival rates for anterior resin composite restorations with 58.9% being less than with metal-ceramic crowns (70.3%) [22].

Anterior teeth could be restored with ceramic veneers in a minimal invasive fashion [16, 23]. Failure rates of ceramic laminate veneers made of feldspathic ceramics were reported to be less than 5% at 5 years and 5 to 15% for 10 to 13 years, respectively [24-28]. Type of preparation [29] and dentin exposure affects the long term survival rate of ceramic veneers [29] while material type (feldspathic or glass-ceramic) did not show significant difference when 5 years survival and complication rates were considered [30].

One other clinical protocol in restoring worn anterior teeth is the so called “sandwich approach” that recommends primarily the restoration of palatal substance loss for anterior guidance, using direct or indirect resin composite to the level of former tooth anatomy and vertical dimension [1]. Considering that the erosion is initially observed on the lingual surface, restoring the lingual tooth surface with resin composite allows restoration of labial side with either again with resin composite or ceramic at different time points. Although individual information is available in clinical studies with regards to the performance of resin composite or ceramic veneers [26, 31], to date mechanical durability of sandwich approach has not been investigated also focusing on the preparation type. The lack of information on this topic complicates clinical decision making between invasive and less invasive therapy options along with the suitable material choice.

The objectives of this study therefore were to compare the load bearing capacity of different treatment modalities for restoring severely worn anterior teeth using different crown and veneer materials and evaluate the failure types based on their reparability. The null hypothesis tested was that all restoration types, regardless of the preparation design and materials used would show no statistically significant difference in terms of fracture strength.

Materials and Methods

The brands, chemical compositions, manufacturers and batch numbers of the materials used in this study are listed in Table 1.

Specimen preparation

Sound human maxillary incisors (N=108) (length: 6.77 - 11.94 mm; width: 5.67 to 9.98 mm), free from restorations and root canal treatment were collected. All teeth used in the present study were extracted for reasons unrelated to this project. Written informed consent for research purpose of the extracted teeth was obtained by all donors prior to extraction according to the directives set by the National Federal Council. Ethical guidelines were strictly followed and irreversible anonymization was performed in accordance with state and Federal Law [32-34]. After tissue remnants were removed with an ultrasonic scaler (Piezon Master 00, EMS, Switzerland), the teeth were stored in 0.5% Chloramin T at 5°C for 4 months until the experiments. After classifying the teeth based on their coronal dimensions (width and length) and root length, they were randomly assigned to 9 groups. The teeth with labial area less than 53 mm² were excluded.

The roots of the teeth were embedded in a polyvinyl chloride (PVC) mould using auto-polymerizing acrylic resin (Scandiquick, Scandia, Hagen, Germany) up to 1 mm above the mid-facial extent of the cemento-enamel-junction (CEJ). Impressions of the intact teeth were made using silicone (Optosil, Lab Putty, Heraeus Kulzer, Hanau, Germany) and in the labio-lingual direction. The silicone keys were used for controlled tooth preparation and used as reference for restoring the teeth to their original tooth shape and dimensions.

Simulation of erosive wear

Except for the control group (Group 1), coronal length of each tooth was shortened 3 mm from incisal resulting in coronal length longer than 2 mm for all teeth and preparation was made on the lingual side simulating substance loss through erosive wear [1]. Palatal reduction was performed using a diamond wheel (15 mm x 3 mm). Initially using a diamond round bur with 1.5 mm diameter, indentations were created at three positions on the palatal area that served as marks for reduction depth control. This procedure resulted

a standardized substance loss with complete dentin exposure. Individual tooth preparations and restorations were as follows for each indication in Groups 2 to 9:

tooth preparations and restorations

Group 1: Intact teeth received no preparation and acted as the control group.

Group 2: Bevel preparation was made on the labial surface in enamel with 1.5 mm length and minimal enamel bevel on the palatal and approximal sides. After etching with 37% H₃PO₄ for 60 s, the enamel surface was conditioned using etch-and-rinse adhesive system (Syntac Classic, Ivoclar Vivadent, Schaan, Liechtenstein) according to the manufacturer's instructions (Table 2). The teeth were reconstructed to their former shape by the silicone index as a reference, incrementally using resin composite (Empress Direct, Shade A3 Enamel, Ivoclar Vivadent) [35]. Each increment was photo-polymerized for 20 s using an LED polymerization device (Bluephase, Ivoclar Vivadent, light intensity: 1100 mW/cm²) from a distance of 2 mm. Final restorations were polished with silicon impregnated rubber brushes (Astropol, Ivoclar Vivadent).

Group 3: In this group, lingual surfaces of the teeth were not prepared and labial surfaces were reduced 0.5 mm in the enamel only, while the incisal surface was partially in dentin. For each tooth, models were obtained made of dental stone (Fujirock, GC, Tokyo, Japan). After isolating them with separation medium (Iso-K, Dandulor, Glattpark, Switzerland), indirect resin composite veneers were processed using a highly filled polymeric material (G.aenial, GC, Tokyo, Kuraray) in a laboratory polymerization device (Heraflash, Heraeus Kulzer, Hanau, Germany) for 120 s. The cementation surfaces were silica coated (30 µm SiO₂, CoJet, 3M ESPE, St. Paul, USA) at 2 bar pressure from a distance of 10 mm for 10 s, silanized (Monobond Plus, Ivoclar Vivadent) and allowed to react with the surface for 60 s. Thereafter adhesive resin (Heliobond, Ivoclar Vivadent) was applied and the indirect composite veneers were adhesively cemented on the lingual side without extending towards the overlap using dual-polymerized resin cement (Variolink II, Ivoclar Vivadent) that was then photo-polymerized from 5 different directions (labial, mesial, distal, occlusal, lingual). Impressions were made from lingually veneered teeth and casts were made using a phosphate-bonded refractory die material (Orbit Vest, GC). Labial veneers were made of feldspathic ceramic (Shade D A3 and

060, Creation, Cendres Métaux, Biel, Switzerland) and sintered according to the manufacturer's instructions. After removing the investment material from the ceramic surfaces by air-abrasion (50 µm Al₂O₃, Corox, Bego, Bremen, Germany) at 0.5 bar pressure, they were finished and polished and glazed. Subsequently, labial enamel surfaces were etched with 37% H₃PO₄ for 60 s, and conditioned using the adhesive system (Syntac Classic). Feldspathic ceramic veneers were etched with 5% hydrofluoric acid (IPS Empress Ceramic Etching Gel, Ivoclar Vivadent) for 60 s and then ultrasonically cleaned (Vitasonic, VITA Zahnfabrik, Bad Säckingen, Germany) for 1 min in distilled water. Then, silane and adhesive resin were applied accordingly. Ceramic veneers were adhesively cemented on the labial surface using the same materials and protocol described for the indirect resin composite veneers.

Group 4: In this group, lingual and labial veneer materials, cementation protocols were identical as in Group 3 except that ceramic veneer did not overlap lingually and lingual backing was only restored with indirect resin composite veneer.

Group 5: In this group, labial veneer material and cementation protocols were identical with the Group 4 except that lingual backing was only restored with direct resin composite incrementally (IPS Empress Direct, Ivoclar Vivadent) as in Group 2.

Group 6: Circumferential preparations of 0.6 mm in depth were made in enamel. Two-piece feldspathic veneers were processed, conditioned and cemented on the lingual and subsequently on the labial surfaces as described in Group 3.

Group 7: In this group, preparation was identical with the Group 6 but instead of two-piece veneers, one piece crown was fabricated made of feldspathic ceramic and adhesively cemented as described in Group 3.

Group 8: Circumferential preparations of 1.2 mm in depth were made on the teeth. Crowns made of metal-ceramic were cemented using conventional glass ionomer cement (Ketac Cem, 3M ESPE). Metal frameworks in this group were made of high gold alloy (Esteticor Special, Cendres & Métaux) and the veneering from feldspathic ceramic (Creation, Cendres & Métaux). Prior to cementation, the intaglio surfaces of the crowns were air-abraded (50 µm Al₂O₃) and ultrasonically cleaned for 1 min in distilled water.

Group 9: Preparation type in this group was identical with the Group 8 but the crowns were made of lithium disilicate all-ceramic according to the manufacturer's instructions and cemented adhesively as described in Group 3. Etching duration with 5% hydrofluoric acid was 20 s.

Specimens in each group were stored in distilled water at 37°C for 24 h prior to testing.

Fracture test and failure analysis

The specimens were then mounted in the jig of the Universal Testing Machine (Zwick ROELL Z2.5 MA 18-1-1/7, Ulm, Germany) at an angle of 105°. A 0.5 mm tin foil was placed on the tooth to avoid punctual loading and repositioning of the stainless steel loading cell. Loading was performed at a crosshead speed of 1 mm/min. Total failure was defined when 30% decrease was reached in the applied load.

Failure types were analyzed and classified as follows: Score 1a-b: No visible fracture of the veneers with (1a) or without root fracture (1b), Score 2a-b: Cohesive fracture within the veneer material without tooth involvement (2a) or with tooth fracture with more than ½ of the surface (2b), Score 3: Only crack formation without debonding of the veneer, Score 4: Partial or total adhesive delamination of the veneer material from the tooth surface. Scores 1a and 2b were further classified irreparable and the other scores as repairable.

Statistical analysis

According to the two-group Satterthwaite t-test (SPSS Software V.13 for Windows, Chicago, IL, USA) with a 0.05 two-sided significance level, a sample size of 12 in each experimental group was calculated to provide more than 62% power to detect a difference of 205 N between mean values. Kolmogorov-Smirnov and Shapiro-Wilk tests were used to test normal distribution of the data. As the data were normally distributed, one-way ANOVA followed by Scheffe and Bonferroni post-hoc tests were applied to analyze possible differences between the groups where the fracture strength was the dependent variable and restoration modalities (9 levels) independent variables. Following Anderson-Darling tests, maximum likelihood estimation without a correction factor was used for 2-parameter Weibull distribution to interpret predictability and reliability of adhesion (Minitab Software V.16, State College, PA, USA). P values less than 0.05 were considered to be statistically significant in all tests.

Results

Restoration modality of simulated worn anterior teeth showed significant differences in mean fracture strength ($p=0.000$).

Groups 1 (558 ± 278), 4 (561 ± 218), 8 (630 ± 252) and 9 (880 ± 319) were significantly higher than those of other groups (348 ± 101 - 421 ± 162) ($p<0.05$) (Table 3). Lingual veneering with direct/indirect resin composite or ceramic did not significantly affect the results ($p>0.05$) but lingual overlap with indirect composite increased the results ($p<0.05$).

Weibull modulus was the highest for Group 5 ($m=3.94$) compared to other groups ($m=2.26$ - 3.22).

Group 1 (12 out of 12), 2, 4 (11 out of 12) and 5 (10 out of 12) presented the highest incidence of repairable failures.

Discussion

This study was undertaken in order to compare the load bearing capacity of minimal invasive to invasive treatment modalities for restoring severely worn anterior teeth using different crown and veneer materials. Based on the results of this study since there were significant differences between the groups, the null hypothesis tested could be rejected.

Tissue loss in teeth due to wear or erosion occurs gradually starting often from lingual, labial or incisal aspects depending on the aetiology, and in severe situations from all aspects. Wear starting from lingual or labial surfaces gradually overlaps the incisal parts of the teeth. Thus, treatment strategy varies depending on the severity and amount of tissue loss that constitutes the reason for comparing durability of different therapy options in this study. While direct application of resin composite materials require practically no tooth preparation and could be accomplished in one session without the need of laboratory work, they could be considered as the least invasive and the most economic option.

Among invasive therapy options, namely the crowns made of feldspathic ceramic, metal-ceramic or lithium disilicate, the latter two presented significantly higher results than those of minimal invasive options and

imilar results compared to intact teeth. When evaluating these results, it has to be noted that fractures in intact teeth were primarily within the enamel and in the metal-ceramic crown group within the veneering ceramic. Hence, the values obtained do not represent the fracture load needed to fracture the tooth itself or the metal framework of the metal-ceramic crowns. The favourable bond strength of the resin cement to both the tooth and the intaglio surfaces of the lithium disilicate crowns [36] along with the higher elasticity modulus of this ceramic could be considered as the reasons for higher fracture strength than the crowns made of feldspathic ceramic (Group 7). In that respect, material properties seemed to be more effective for crown indications more than the design. Accordingly, crowns made of feldspathic ceramic bonded in one piece or bonded in two veneer pieces at the lingual and labial sides of the teeth did not show significant difference. Thus, in case of a ceramic indication, the two-piece option could be considered, as this would delay the complete tooth preparation. Furthermore, the two-piece ceramic veneers resulted in more repairable failures. Generally, the crown options, made of either feldspathic or lithium disilicate presented radial cracks and eventually through fractures. This type of fracture clinically often requires replacement of the crowns. Hence, in case of a need for ceramic crown restorations to achieve harmony with the neighbouring teeth or other ceramic restorations, two-piece veneers could be contemplated. This approach would not necessitate removing the interproximal contact area but possible marginal discoloration should be monitored at the interproximal transition zone [37].

Among all minimal invasive veneer options, when lingual veneer was made of indirect resin composite with an overlap using the same material, the higher fracture strength results were obtained than the opposite scenario where the lingual veneer with the overlap was made of feldspathic ceramic. In spite of the fact that indirect resin composites present lower elasticity modulus than that of feldspathic ceramic, the improved bonded interface in the tooth-cement-indirect composite especially after silica coating and silanization [35,38]. could explain the high results in Group 4 obtained in this study. This type of surface conditioning could be achieved either at the laboratory typically with 110 µm particles or at chairside with 30 µm. In an attempt not to affect the precision, the intaglio surfaces of the indirect resin were conditioned with the latter [39]. With this

oute the adhesive strength of the resin cement to both the enamel/dentin on one side and to the indirect composite on the other delivers bond strength results in the range of 15 to 30 MPa [38, 40, 41].

Similar level of adhesion of the resin cement to both substrates decreases the possibility of early delamination of one of the interfaces. This could then compensate for the low flexural strength or the elasticity modulus of the veneer material [35]. Depending on the percentage of fillers per volume, modern resin based composite materials typically have elasticity moduli between 6 to 15 GPa [42]. According to the manufacturer's information, the indirect resin composite used in this study had elasticity modulus of 6 to 8 GPa being significantly lower than that of feldspathic ceramic (60-70 GPa) and pressed lithium disilicate (96 GPa) [43]. Although information in this regard was not available for the direct resin composite, the non significant difference between groups 3 and 5 indicates that both resin materials had comparable stiffness. In fact, polymerization under heat and pressure in laboratory processed resin composites show higher degree of conversion [44] but this does not necessarily increase their flexural strength [45] compared to those of direct resin composites [46]. On the other hand, ceramic materials with their higher modulus of elasticity were claimed to transfer less stress to the tooth structures compared to resin composite restorations [47]. However, this property could yield to cohesive fracture of the material in ceramic overlapping veneers, which was evident in this study. Nevertheless, the need for overlap is dictated by the dental tissue loss at the incisal edge and the lingual anatomical concavity, which needs to be evaluated individually for each single case [48]. Nonetheless, apart from better mechanical resistance, the choice of direct or indirect resin composites on the lingual side results in less wear on the antagonist teeth [49,50].

Although higher fracture strength values were obtained for the metal-ceramic and lithium disilicate crowns, these groups did not present the highest Weibull moduli with the monolithic option (3.2) being higher than bilayered one (2.9), compared to some of the other groups. This could be attributed to the presence of flaws and technical sensitivity during the whole fabrication process. Interestingly, in group 5, where lingual veneer was direct composite and labial feldspathic ceramic, higher modulus (3.94) was obtained. One explanation for this could be less flaws and better adhesion achieved during incremental build up of the direct resin

composite. These observations should be verified in a larger sample. In this context, power calculations were repeated for future studies and a sample of 18 per group would deliver 80% power to detect the same mean difference of 200 N.

Several studies documented fracture strength of metal-ceramic crowns with similar results obtained in this study [51-53]. However, other studies on metal-ceramics on endodontically treated teeth with a post [52, 55-57] would not be relevant to compare with the results in this study. Likewise, fracture strength values of veneers up to 750 N [54] could not be compared with those in this study since lingual surface of teeth were not restored with veneers and loading was performed directly on enamel. On the other hand, although loading conditions were not identical, where the incisal edge or interface has been loaded, values up to 300 N were reported [44, 58]. Nevertheless, load bearing capacities for all groups were above 300 N exceeding the suggested (150 to 300 N) chewing forces in the anterior region of the mouth [59, 60].

Fracture strength results should be also coupled with the failure type analysis. Except fractures that interfere with appearance that need replacement, practically almost all failure types could be repaired with resin composites and the corresponding surface conditioning methods [39, 61]. Among different failure types, root fracture is of lower or even non clinical relevance that could be due to pre-existing cracks in the extracted teeth or lack of proprioception in the in vitro loading settings. However, a trend towards more irreparable failures was observed when lingual veneers were made of ceramic materials.

In this study, the wear scenario was simulated without involving the acidic challenge encountered in the mouth including buffering solutions like human saliva or artificial saliva. Dental tissues exposed to acidic environment could result in demineralization in deeper levels of dentin [62], a condition that is difficult to simulate in an in vitro setting and could be considered as a limitation of this study. Additionally, the results of this study represent early failures under static loading. Hence, the restoration types tested in this study are currently being investigated under cyclic loading and thermomechanical aging conditions.

Conclusions

From this study, the following could be concluded:

- 1) For the restoration of worn teeth, those crowned with metal ceramic or lithium disilicate presented significantly higher fracture strength values compared to other minimal invasive restoration options, except for the group where lingual surfaces and the overlap were restored with indirect resin composite veneer and the labial with feldspathic ceramic.
- 2) Lingual veneering with direct or indirect resin composite did not show significant difference than those restored with feldspathic ceramic veneer and lingual overlap with indirect composite increased the fracture strength.
- 3) Weibull modulus indicated the highest reliability of strength when lingual veneering was made of direct resin composite and the labial with feldspathic ceramic.
- 4) Direct resin composite veneering both lingually and labially and indirect resin composite on the lingual and ceramic veneer in the labial presented the highest incidence of repairable failures.

Clinical Relevance

For the restoration of severely worn teeth, considering fracture strength, reliability analysis and incidence of repairable failure, complete direct resin composite or lingual veneering with direct/indirect resin composite and labial with feldspathic ceramic could be recommended.

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Conflict of interest

The authors did not have any commercial interest in any of the materials used in this study.

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Captions to tables and figures:

Figure:

Figs. 1a-i Schematic drawings of reconstruction types and materials.

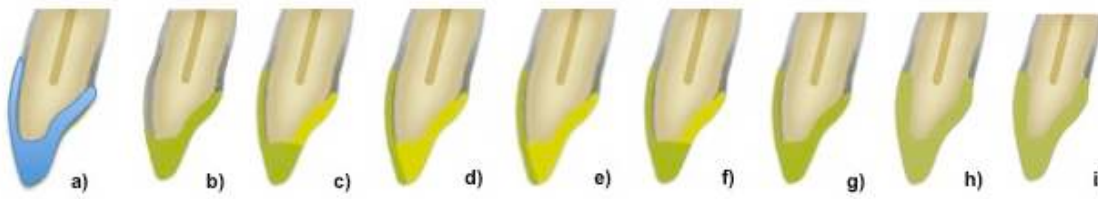
Tables:

Table 1. The brands, manufacturers, chemical compositions and batch numbers of the materials used in this study.

Table 2. Cementation protocol employed on tooth substance and for the veneers and the crown materials in each experimental group. *To avoid unprecise fit of the veneer.

Table 3. The mean fracture strength values (MPa \pm standard deviations), Confidence Intervals (95%), Weibull modulus, distribution and frequency of failure types per experimental group analyzed after fracture strength test: Score 1a-b: No visible fracture of the veneers with (1a) or without root fracture (1b), Score 2a-b: Cohesive fracture within the veneer material without tooth involvement (2a) or with tooth fracture (2b), Score 3: Only crack formation without debonding of the veneer, Score 4: Partial or total adhesive delamination of the veneer material from the tooth surface. *Score 1a-b, and 2b irreparable and the other scores repairable. The same superscript lowercase letters in the same column indicate no significant differences based on the substrate type and uppercase letters based on the test method ($p<0.05$).

Figures:



figs. 1a-i Schematic drawings of reconstruction types and materials. **a)** Group 1: Intact tooth, **b)** Group 2: Direct Resin Composite, **c)** Group 3: Lingual: Indirect composite, Labial: Ceramic, Lingual overlap: Ceramic, **d)** Group 4: Lingual: Indirect composite, Labial: Ceramic, Lingual overlap: Indirect composite, **e)** Group 5: Lingual: Direct composite, Labial: Ceramic, **f)** Group 6: Lingual: Ceramic, Labial: Ceramic, **g)** Group 7: Feldspathic Ceramic Crown, **h)** Group 8: Metal-ceramic Crown, **i)** Group 9: Lithium Disilicate Crown.

Tables:

Brand	Manufacturer	Chemical composition	Batch number
Scandiquick	Scandia, Hagen, Germany	Polymethylmethacrylate	Liquid: 040125 Powder: 240125
Esteticor special	Cendres & Métaux, Biel, Switzerland	High-gold-alloy (77.3%), Ag, Pt , Pd, Cu, Fe, In, Ir, Se	0000 182002
Ceramicor	Cendres & Métaux	Phosphate-bonded investment compound, containing graphite	Liquid: 0000168251 Powder: 90801
Creation D (A3)	Cendres & Métaux	Feldspatic ceramic	9956
Creation S (060)	Cendres & Métaux	Feldspatic ceramic	9479
Glaze Liquid	Cendres & Métaux	Glazing liquid for ceramics	1064
Carat modelling liquid	Hager Werken, Duisburg, Germany	Modelling liquid for ceramics	604216
Opaquer	Cendres & Métaux	Opaquer mass	
G.aenial	GC, Tokyo, Japan	Mixture of urethane dimethacrylate, dimethacrylate co-monomers, fumed silica, fluoro-alumino-silicate, silica, strontium-glass, lanthanoid-fluoride, pigments and photo-activator/catalysts	0912211
Orbit vest	GC	Phosphate-bonded refractory die material	1010251
Optosil Lab Putty	Heraeus Kulzer, Hanau, Germany	C-polysiloxane Silicone	0174222
Syntac classic primer	Ivoclar Vivadent, Schaan, Lichtenstein	Acetone 25-50%, Triethylenglycoldimethacrylate 10-<25%, Polyethylenglycoldimethacrylate 3-<10%, Maleic acid (3-<10%)	N11162
Syntac classic adhesive	Ivoclar Vivadent	Polyethylenglycoldimethacrylate 25-50%, Glutaraldehyde 3-<10%	N11161
Heliobond	Ivoclar Vivadent	bis-GMA (50-100%), Triethylenglycoldimethacrylate (25-50%)	N75604 (bond)
MonoBond Plus	Ivoclar Vivadent	Monomer: <1.5% Methacrylate, Phosphoric acid ester Solvent: Ethanol (96%)	P20536
VarioLink II	Ivoclar Vivadent	Dimethacrylates, inorganic fillers, ytterbiumtrifluoride, initiators, stabilizers and pigments	P22989
IPS Speed vest	Ivoclar Vivadent	Phosphate-bonded investment compound for ceramics	Liquid: HL3041 Powder: PL3060
IPS e.max press	Ivoclar Vivadent	Lithium disilicate press ceramic	N75604
IPS Empress Direct	Ivoclar Vivadent	Urethane dimethacrylate, tricyclodocane dimethanol dimethacrylate, bis-GMA, Ytterbium	P34518

		trifluoride, Ba-Al-fluorosilicate glass, prepolymer, pigments and catalysts	
IPS Empress ceramic etching gel	Ivoclar Vivadent	5% Hydrofluoric acid	P26213
Total etch	Ivoclar Vivadent	37% H ₃ PO ₄	N11162
Ketac cem	3M ESPE	Water, polycarboxylic acid, tartaric acid, glass powder, pigments and conservation agents	352671

Table 1. The brands, manufacturers and chemical compositions and batch numbers of the main materials used in this study.

Groups	Adhesive / Cementation mode	Polymerization
2	Syntac Classic	Photo-polymerization for 20 s for each increment in bonded tooth
3/4	Tooth: Syntac Classic	No polymerization
	Indirect Composite: Monobond Plus	Reaction with the surface for 60 s
	Cement: VarioLink II translucent (low viscosity)	Photo-polymerization for 40 s from 5 directions
5	Tooth: Syntac Classic	Polymerization for lingual direct build-up No polymerization for labial veneering made of ceramic*
	Ceramic: Monobond Plus	Reaction with the surface for 60 s
	Adhesive: Heliobond	No polymerization
	Cement: VarioLink II translucent (low viscosity)	Photo-polymerization for 40 s from 5 directions
6/7	Tooth: Syntac classic	No polymerization
	Ceramic: Monobond Plus	Reaction with the surface for 60 s
	Adhesive: Heliobond	No polymerization
	Cement: VarioLink II translucent (low viscosity)	Photo-polymerization for 40 s from 5 directions
8	Ketac cem	Chemical polymerization
9	Tooth: Syntac Classic	No polymerization
	Ceramic: Monobond Plus	Reaction with the surface for 60 s
	Adhesive: Heliobond	No polymerization*
	Cement: VarioLink II translucent (low viscosity)	Photo-polymerization for 60 s from 5 directions

Table 2. Cementation protocol employed on tooth substance and for the veneers and the crown materials in each experimental group. *To avoid unprecise fit of the veneer.

Groups	Fracture Strength (Mean ± SD)	Min-Max (95% CI)	Weibull modulus (<i>m</i>) (95% CI)			Failure type distribution (n)				
			<i>m</i>	Scale	CI	Score 1a/1b	Score 2a/2b	Score 3	Score 4	Repairable/ Irrepairable
1	558 ± 278 ^b	251-1075 (381-735)	2.26	633.45	(1.47-3.47)	0/0	0/0	4	8	12/0
2	421 ± 162 ^a	231-801 (318-525)	2.84	473.38	(1.88-4.29)	1/0	4/0	7	0	11/1
3	371 ± 135 ^a	65-580 (286-457)	3.22	411.35	(2-5.15)	0/1	4/1	4	2	11/1
4	561 ± 218 ^b	178-944 (405-716)	3.01	627.72	(1.83-4.96)	0/1	1/1	9	0	11/1
5	348 ± 101 ^a	184-520 (283-412)	3.94	384.4	(2.54-6.11)	0/0	1/2	9	0	10/2
6	389 ± 144 ^a	116-650 (297-481)	3.13	434.64	(1.99-4.91)	0/1	0/5	6	0	5/7
7	350 ± 132 ^a	182-639 (266-433)	2.95	392.2	(1.94-4.5)	1/0	1/6	4	0	2/10
8	630 ± 252 ^b	190-990 (469-790)	2.91	707.55	(1.83-4.65)	0/4	0/7	1	0	7/5
9	880 ± 319 ^b	458-1405 (665-1094)	3.2	985.2	(2-5.1)	2/1	2/7	0	0	9/3

Table 3. The mean fracture strength values (MPa ± standard deviations), Confidence Intervals (95%), Weibull modulus, distribution and frequency of failure types per experimental group analyzed after fracture strength test: Score 1a-b: No visible fracture of the veneers with (1a) or without root fracture (1b), Score 2a-b: Cohesive fracture within the veneer material without tooth involvement (2a) or with tooth fracture (2b), Score 3: Only crack formation without debonding of the veneer, Score 4: Partial or total adhesive delamination of the veneer material from the tooth surface. *Score 1a-b, and 2b irreparable and the other scores repairable. The same superscript lowercase letters in the same column indicate no significant differences based on the substrate type and uppercase letters based on the test method ($p < 0.05$). For group descriptions see Figs. 1a-i.